Adaptation and mitigation as complementary tools for reducing the risk of climate impacts

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Abstract This paper uses the likelihood of flooding along Brahmaputra and Ganges Rivers in India to explore the hypothesis that adaptation and mitigation can be viewed as complements rather than sustitutes. For futures where climate change will produce smooth, monotonic and manageable effects, adopting a mitigation strategy is shown to increase the ability of adaptation to reduce the likelihood of crossing critical threshold of tolerable climate. For futures where climate change will produce variable impacts overtime, though, it is possible that mitigation will make adaptation less productive for some time intervals. In cases of exaggerated climate change, adaptation may fail entirely regardless of how much mitigation is applied. Judging the degree of complementarity is therefore an empirical question because the relative efficacy of adaptation is site specific and path dependent. It follows that delibrations over climate policy should rely more on detailed analyses of how the distributions of possible impacts of climate might change over space and time.

Keywords Adaptation Climate change impacts Climate change risks Flood control Intolerable changes Mitigation Risk management

1 Introduction

Many studies have focused on the damages caused by climate change and climate variability that might be avoided by mitigation. Their content is chronicled in the contributions of Working Groups II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2001a, 2001b) as well as in the more recent survey authored by Smith and Hitz (2004). Estimates of damages avoided are certainly critical pieces of information for decision-makers who are contemplating global responses to climate change from a cost-benefit perspective, but concern must be raised about the ability of the research community to produce reliable estimates of net global benefits that a cost-benefit approach requires. If the research community is honest in its self-assessment of the current state of knowledge, then it will recognize that current deliberations of climate policy should rely more heavily on analyses that report how the distributions of possible impacts of climate might change over space and time. Why? Because portraits of these distributions can sustain a more informed understanding of climate-related risks than estimates of net global risks and because adaptation and hedging is best done at a local or regional level where descriptions of risk can more accurately reflect characteristics that are path dependent and site specific. Researchers and decision-makers should, as a result, move towards accepting a different decision-analytic approach to the climate issues. In this short paper, in fact, we propose that both communities begin to frame their discussions of near and medium-term climate policy in terms of strategies designed explicitly to manage risk.

We are, of course, not alone in making this point. Jones (2003), Harremoes (2003), Yohe et al.

(2004) and others have proposed that the design of climate policy be framed as a risk-management problem in which near to middle-term interventions are offered as part of a hedging strategy designed to diminish the likelihood of suffering intolerable outcomes in the future. What sort of information would be required to inform decisions based on such an approach? Some description of possible intolerable outcomes (thresholds beyond which the impacts of climate change and variability become so severe that systems cannot adapt adequately) would certainly be required. So would some understanding about how adaptation might alter the boundaries of intolerable change (by reducing exposure or sensitivity), some description of the sensitivity of the likelihood of crossing these amended thresholds to changes in climate variables, and some quantifiable understanding about how mitigation might influence the distribution of those variables.

Can the research community meet these requirements? This paper answers this question in the affirmative by offering two illustrations of how. Section 1 begins by displaying a risk-based structure in an artificial environment and offering support for the hypothesis that adaptation and mitigation can actually complement one another in an effort to reduce climate-related risk. Section 2 moves to an applied example that builds on earlier work by Yohe and Strzepek (2004). Using output derived from the COSMIC program developed by Schlesinger and Williams (1998 and 1999), we examine the effect of directing mitigation policy to specific concentration targets on the relative efficacy of a flood-control adaptation along the Brahmaputra and Ganges Rivers in India across a range of ''not-implausible'' climate futures.[1] More specifically, we compare the likelihood of modest, moderate and severe flooding along unregulated trajectories of climate change with comparable likelihoods along the Wigley et al. (1996) least cost emissions scenarios (the WRE scenarios) that hold effective concentrations of greenhouse gases to 450, 550 650 parts per million (ppm) and the earlier IPCC 550 ppm. trajectory. Having thereby demonstrated one method by which the research community can explore the effect of mitigation on the distribution of a climate impact, our concluding remarks reflect on the degree to which our results support the hypothesis that adaptation and mitigation can complement one another in our attempts to cope with future climate change.

2 An illustrative case—the complementarity of adaptation and mitigation

If the double causality between global climate change and observed local impacts could be established, then both adaptation and mitigation could work to reduce the risk associated with climate change. Both policy approaches would hold the potential of reducing the likelihood that one community (in the case of a local manifestation of climate change) or many communities (in the case of a discontinuity in the global climate system like the shutdown of the thermohaline circulation) would experience intolerable impacts. In this approach to climate policy, mitigation and adaptation are complements (in the strict sense of one being able to increase the marginal productivity of the other) because mitigation can reduce the likelihood component of a risk calculation (exposure) while adaptation can work to reduce the impact component (sensitivity).

The various panels of Fig. 1, exported from Yohe and Burton (2004), illustrate this point in an artificial environment. Panel A casts a time series of variability around an upward secular trend in some arbitrary climate variable against the boundaries of a system's coping range. Notice that the system experiences 18 time periods outside of its coping range. The majority of these episodes occur late in the series, but the near-term is not devoid of uncomfortable periods. Panel B displays the effect of mitigation which reduces both the trend and the inter-period variability; it reduces the likelihood of the system's finding itself outside of its coping range over the designated time span from 36 to 24% (now only 12 time periods outside the coping range). Panel C shows the effect of an adaptation that expands the upper boundary of the coping range by investing in an adaptation policy or project that is completed by the sixth period; the likelihood of moving beyond this expanded coping range is 20% (10 time periods in fifty). Panel D combines the two policies, and shows the likelihood falls to 14%, and all of the episodes occur after the 40th time period.

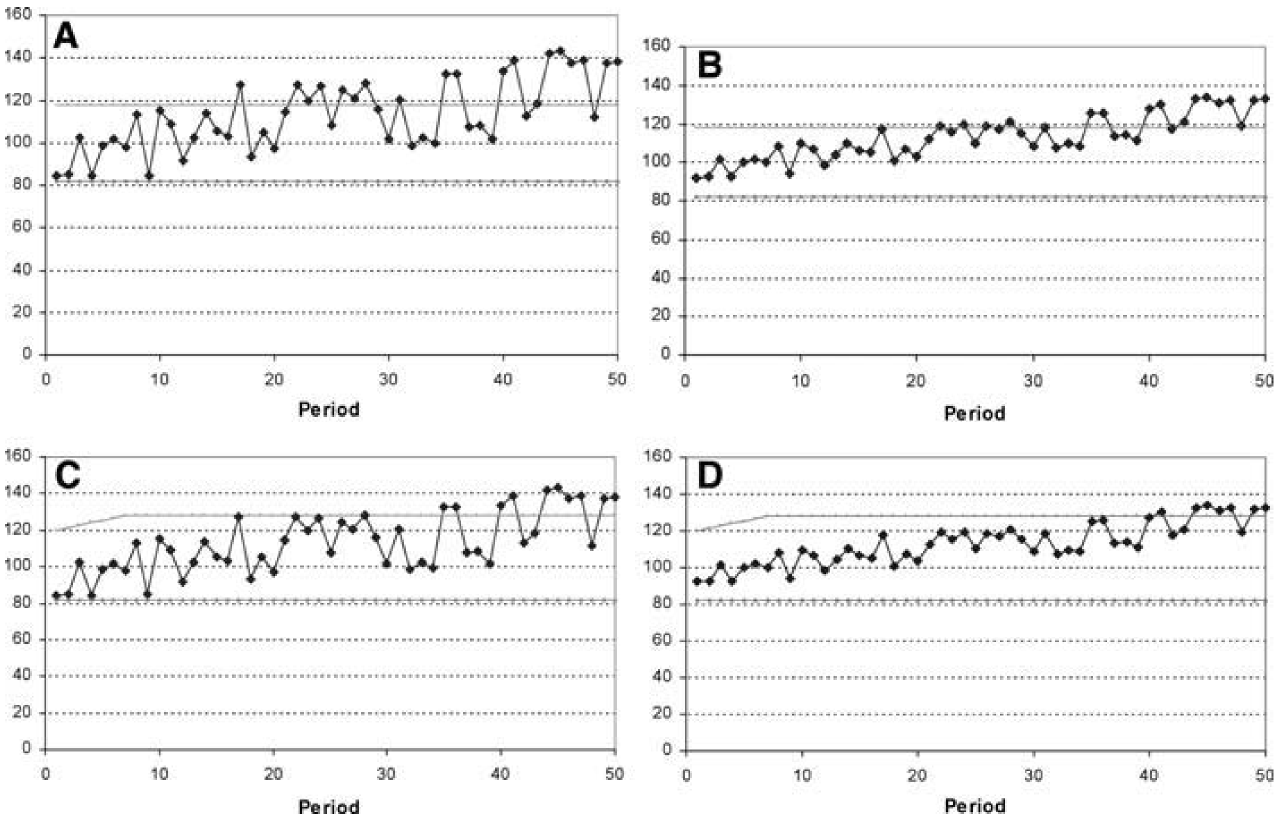


Fig. 1 Panel A: A baseline illustration of climate variability cast against a coping range; the boundaries of the coping range are exceeded in 18 of the 50 time periods. **Panel B:** The effect of a mitigation process that reduces variability and long-term trend; the boundaries of the coping range are exceeded in 12 of the 50 time periods. **Panel C**: The effect of an adaptation that expands the upper boundary of the coping range by the end of the 6th period; the boundaries of the coping range are exceeded in 10 of the 50 time periods. **Panel D:** The effect of both mitigation and adaptation; the boundaries of the coping range are exceeded in only 7 of the 50 time periods and none before the 40th

3 An applied illustration—flooding in Southeast Asia

Bangladesh is very vulnerable to flooding, principally due to intense monsoon precipitation that falls on the watershed of the Ganges, Brahmaputra and Meghna (GBM) Rivers. Mirza (2003) reports that the GBM watershed covers 1.75 million square kilometers of Bangladesh, China, Nepal, India and Bhutan. According to Ahmed and Mirza (2000), 20.5% of the area of Bangladesh is flooded each year, on average; and in extreme cases, floods about 70% of Bangladesh can be under water. The goal of this section is to analyze the impact of mitigation across a range of not-implausible climate change scenarios defined in terms of the frequency of flooding in Bangladesh.

Mirza (2003) took a statistical approach to relate monsoon precipitation to peak flood flows. This paper uses a conceptual hydrologic rainfall-runoff model that incorporates evapotranspiration, snowmelt, soil moisture and surface and sub-surface flows. Separate models of the Ganges and Brahmputra Rivers were developed; they are described in the appendix. The hydrologic model needs to be driven by a climate data, of course, so we calibrated both models to spatially averaged climate change variables of the sort reported by COSMIC.[2] To cope with this problem, Nepal was selected as the representative country for three reasons. First of all, Nepal is located almost directly in the geographic center of the GBM watershed. Second, its monsoon precipitation characteristics, in quantity and timing, are representative of the average characteristics over much of the GBM basins. Conversely, the average COSMIC data from China or India were not representative of the conditions in the GBM watershed.

Schlesinger and Williams (1998 and 1999) designed the COSMIC program so that researchers could produce literally thousands of ''not-implausible'' climate scenarios that are internally consistent. Each scenario can be defined by a specific global circulation model (of the 14 GCM's included in COSMIC) driven by one of seven unregulated or ten regulated emissions scenarios for greenhouse gases. The unregulated trajectories span virtually the entire range of published trajectories, and the regulated trajectories conform to either the WRE or IPCC pathways to five different concentration targets. Each scenario can also be defined in terms of associated sulfate emission trajectories (with a forcing parameter prescribed between 0 and 1.2 watts per meter squared) and in terms of a climate sensitivity set somewhere between 18 and 4.58. Recall that climate sensitivity specifies the equilibrium increase in global mean temperature that would be associated with a doubling of effective carbon-dioxide concentration from pre-industrial levels.

It would be imprudent if not impossible to conduct integrated analyses along every possible combination of emissions and climate parameters, of course, so there is a fundamental need to limit the number of scenarios under study while still spanning the range of ''not-implausibility''. In this application, six scenarios were chosen and dubbed ''representative'' of an underlying set of 126 possibilities—an original set of futures that spanned three emissions scenarios (low to high) and three climate sensitivities (1.5, 2.5 and 4.5 degrees) across all 14 GCM's. Since the mitigation scenarios included in COSMIC do not account for sulfate emissions, however, sulfate forcing was set equal to zero in every case.

Fig. 2 depicts the time trajectories of river flow through 2075 for each of the six representative cases; Table 1 reveals the underlying particulars of these representatives. Care must be taken in interpreting these trajectories, however. They were not chosen to be representative of how the future might unfold in terms of river flow in any statistical sense. They were chosen, instead, to represent the diversity displayed by the complete set of internally consistent ''not-implausible'' climate futures that published climate models could produce. Two of the scenarios are relatively benign in the sense that river flow is stable or increases only modestly through the year 2075.

Two others show dramatic increases—Scenario 6 almost immediately and Scenario 5 in the second half of the century. The two remaining scenarios display 50% increases in river flow through 2025, but then they diverge. Scenario 3 declines in the middle of the century while Scenario 4 levels out before beginning another period of increase past 2050.

The various panels of Fig. 3 display the results of applying 4 alternative mitigation paths to each of the six representative scenarios. For each representative scenario, the top graphs contrast river flow along an unregulated trajectory with outcomes derived from COSMIC for three WRE mitigation strategies (450, 550 and 650 parts per million targets for effective greenhouse gas concentrations); these are the 450A, 550A and 650A pathways, respectively. Trajectories for one of the original IPCC mitigation strategies (targeted at 550 ppm and identified as S550) are also displayed. The remaining three graphs for each scenario portray the same results in terms of the annual likelihood of suffering an episode of modest, moderate, or severe flooding.

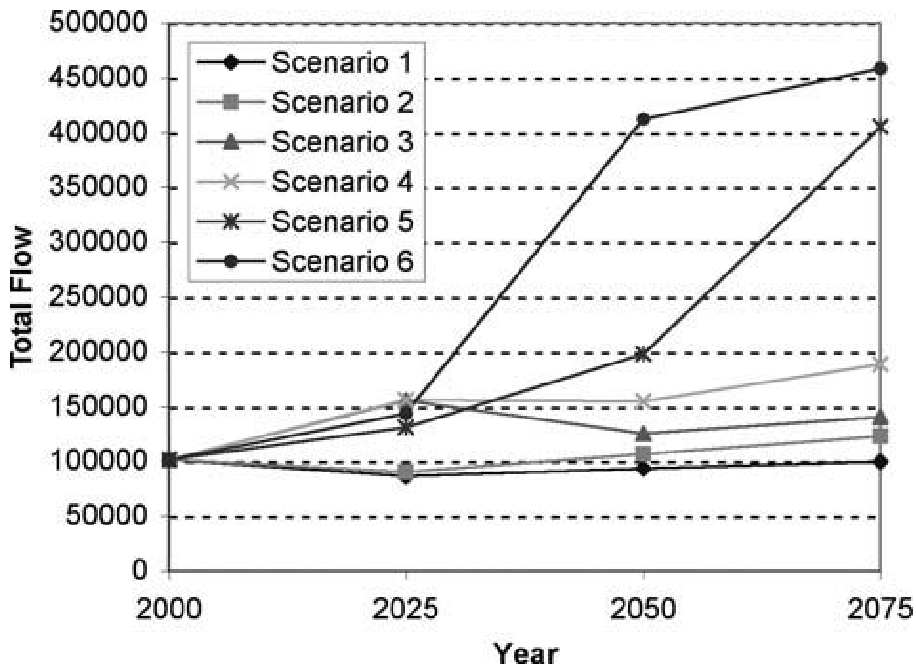


Fig. 2 Selection of the representative scenarios and their time trajectories in terms of annual flow through 2075

Table 1 Characterizing the representative scenarios for the years 2050 and 2100

Scenario	Global circulation model [a]	Climate sensitivity	Emissions scenario[b]
1	GFQF	2.5°	S3 (520;678)
2	POLLS	4.5°	S5 (611;912)
3	HEND	2.5°	S5 (611;912)
4	CCC	2.5°	S5 (611;912)
5	UIUC	2.5°	S5 (611;912)
6	UIUC	4.5°	S5 (611;912)

Notes: [a] The various GCM's are identified in full in Schlesinger and Williams (1998)

[b] The emissions scenarios are displayed in Yohe (1996) where the underlying parameterizations are specified. The numbers in the parentheses indicate effective concentrations of greenhouse gases in carbon dioxide equivalents for the years 2050 and 2100

Several observations are now at hand. Notice, first of all, that the effect of mitigation is usually but not always positive, in the sense that more stringent reduction of greenhouse gas concentrations over time will reduce the likelihood of flooding in any particular year. Mitigation tends to be beneficial when climate change produces monotonic increases in flow over time, but can work to delay peak flow years along scenarios where flow actually declines for some time intervals. In these cases, mitigation can actually increase flow and thus the likelihood of flooding for some years and not others. Comparisons of the 550A and S550 scenarios also reveal that the timing of mitigation can make a difference. Since the S550 policy trajectory restricts greenhouse gas emissions more strenuously in the early years, it seems to have a stronger effect in reducing the likelihood of flooding along most scenarios where unregulated river flow increases monotonically over time. Finally, Scenarios 5 and 6 indicate that there are ‘‘not-implausible’’ climate futures for which the potential benefits of mitigation can be overwhelmed by climate change because even modest increases in concentrations cause dramatic increases in river flow.

Figure 4 finally turns our attention to the relative efficacy of an adaptation strategy along the various mitigation pathways.[3] We consider, in particular, the degree to which building protection along the riverbed to prevent moderate flooding will actually reduce the likelihood of moderate flooding (since this protection would still be overwhelmed during episodes of severe flooding). More strenuous mitigation (derived from lower concentration targets like 450 ppm instead of 550 ppm or from larger emissions reductions in the near-term along S550 instead of 550A) generally improves the ability of this adaptation to reduce the chance of flooding. There are exceptions to this conclusion, though, along Scenario 3 (where river flow climbs and then falls over time) and along Scenario 6 (where increased flow overwhelms the river system for any mitigation strategy). Notice, though, that adaptation can be effective even late in the century along Scenario 5 if mitigation targeted at 450 ppm or 550 ppm along the IPCC pathway were applied. Within limits, therefore, mitigation complements adaptation in the strict sense of improving its ‘‘marginal productivity’’.

Fig. 3 Total flow and the associated likelihoods of modest, moderate and severe flooding, respectively

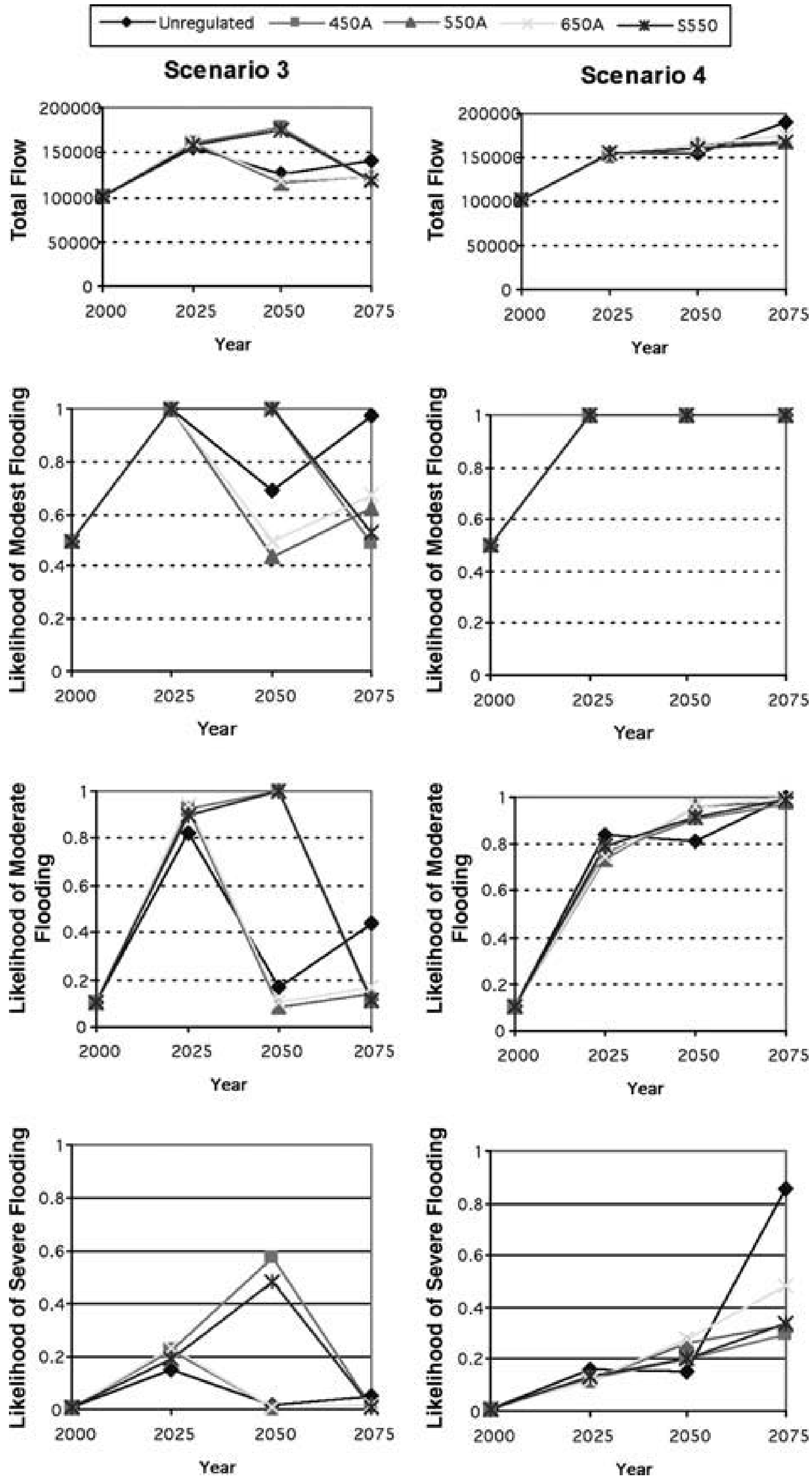
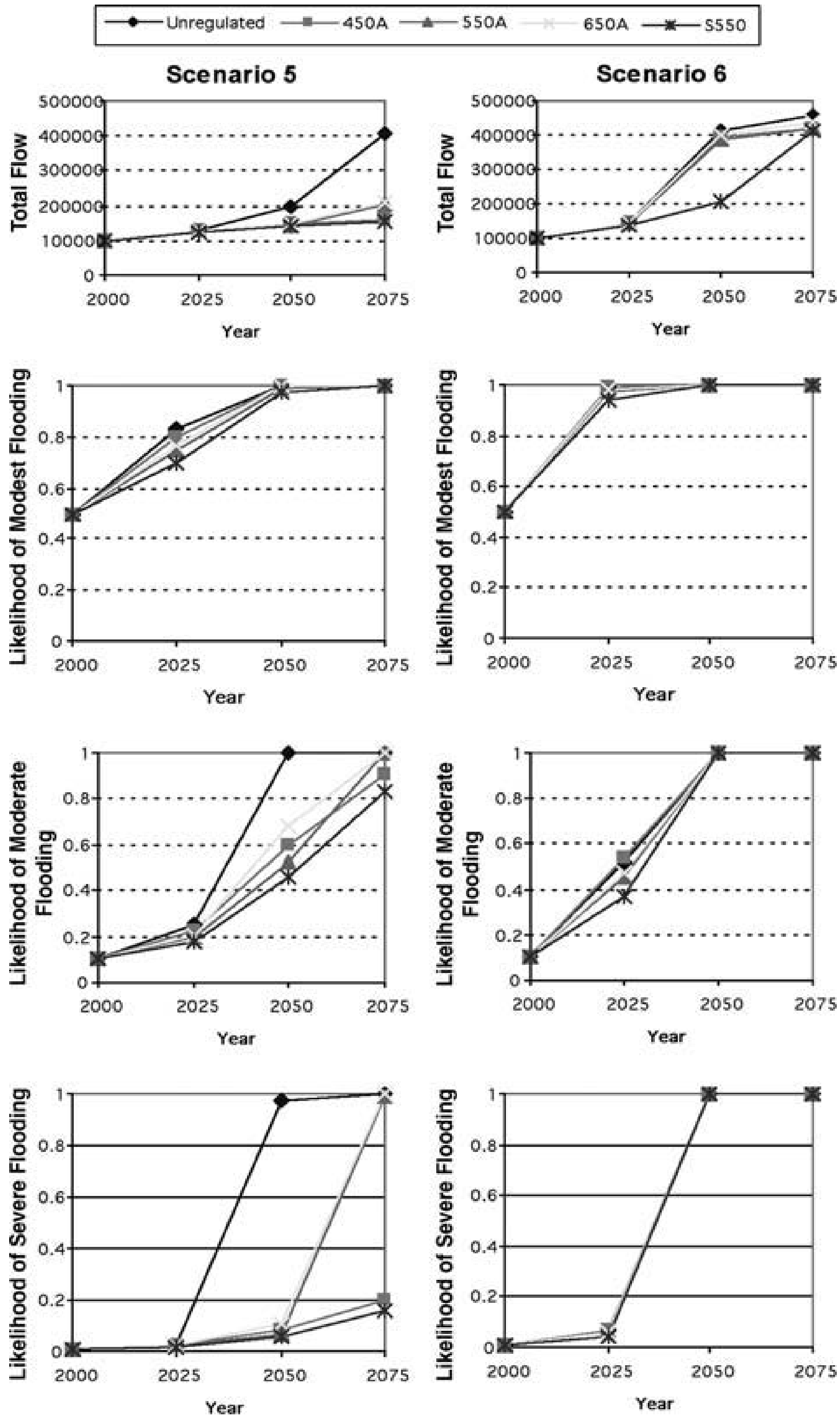


Fig. 3 Total flow and the associated likelihoods of modest, moderate and severe flooding, respectively, cont



4 Concluding remarks

This paper began with the hypothesis that adaptation and mitigation can be viewed as complements rather than substitutes if researchers and decision-makers adopt a risk management approach to policy. We examined the strength of this hypothesis in a particular setting (the likelihood of flooding along the Brahmaputra and Ganges Rivers) across a range of ‘‘not-implausible’’ futures, and we have seen that it is fairly, but not ubiquitously robust. For futures where climate change will produce smooth, monotonic and manageable effects, adopting a mitigation strategy should increase the ability of adaptation to reduce the likelihood of crossing critical thresholds of tolerable climate. By how much? This is an empirical question, both in our case study and in general (because the relative efficacy of any adaptation strategy is site specific and path dependent). For futures where climate change will produce variable impacts over time, we have demonstrated that it is even possible that mitigation will make adaptation less productive for some time intervals. Finally, for futures where climate change will produce enormous impacts, adaptation may fail regardless of how much mitigation is applied.

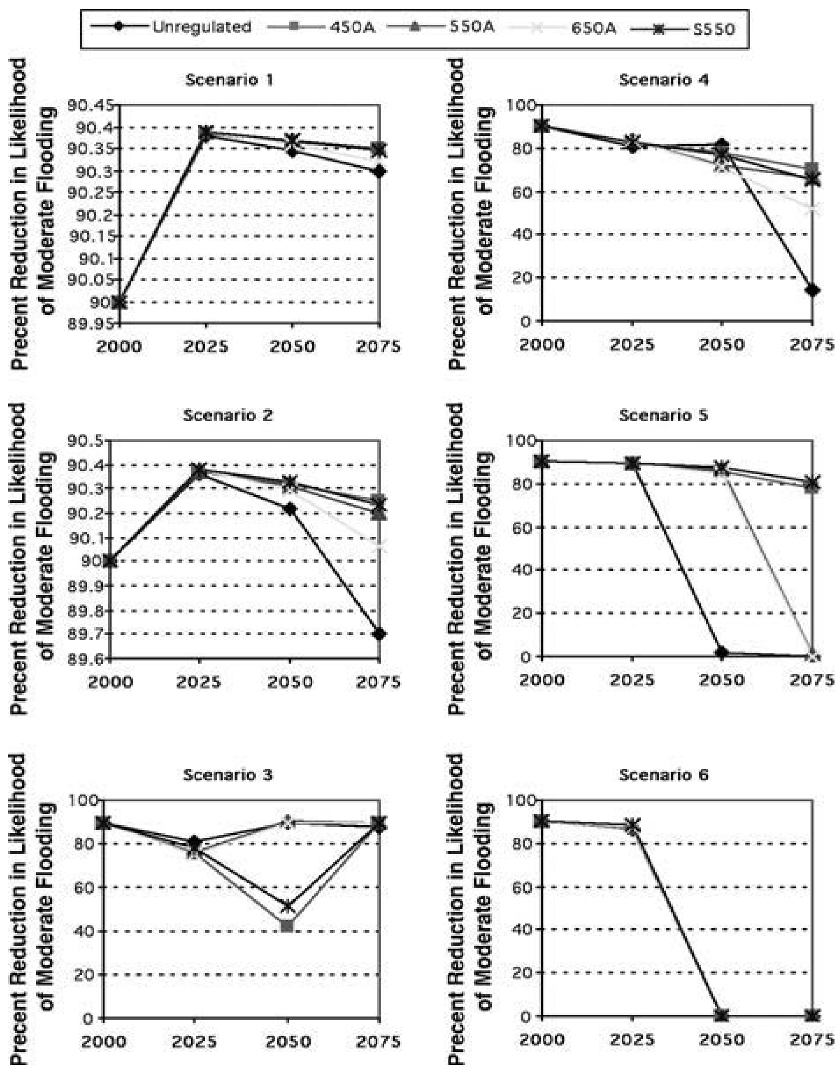


Fig. 4 The effect of protecting along the riverbed against moderate flooding on the likelihood of moderate flooding associated with severe flooding events

Appendix—The hydrologic models [as Described in Yohe and Strzepek (2004)]

Uncertainties in the historical climate record

The COSMIC scenario generator provides a base year of 1990, but does not provide any information on the statistics of climate record for the country. It is nonetheless necessary to have data on the moments and probability distributions of the hydro-climatic variables to perform a flood frequency analysis. To supplement the COSMIC scenario data for Nepal, we employed historical climate data gathered by the Tyndall Center for Climate Change Research and recorded in their TYN CY 1.1 data set. Mitchell et al. (2004) report that the TYN CY 1.1 data provide a summary of the climate of the 20th century for 289 countries and territories including monthly time series data for seven climate variables for the 20th century (1901–2000). Interestingly, the data set creators provide the following warning: ‘‘This data set is intended for use in trans-boundary research, where it is necessary to average climatic behaviour over a wide area into statistics that are representative of the whole area.’’ This warming endorses the use of TYN CY 1.1 and COSMIC data for Nepal as appropriate for this modeling approach.

The TYN CY1.1 monthly time series data for the 20th century (1901–2000) show that mean annual temperature in Nepal varies very little with a COV of 0.04 and a lag-one correlation of 0.47. By way of contrast, precipitation exhibits variability at the total annual level. More importantly for predicting the likelihood of flooding events, though, maximum monthly precipitation per year is even more variable and strongly (positively) skewed with a high coefficient of variation.

The flooded area in Bangladesh varies greatly from year to year. Flood risk is characterized by the probability that a certain level of flood will occur each year. The risk factor is generally express as a return period of T = 1/(probability of occurrence). The return period is determined from the cumulative density function of flood frequency. For flood frequency analyses, FAP (1992) recommends using the Gumbel Type I distribution (EV1) for the major rivers in Bangladesh; it is defined by

$$F(x) = \exp\left[-\exp\left(\frac{x-u}{\alpha}\right)\right] \quad -\infty<x<\infty$$
$$\alpha = \frac{\sqrt{6}}{\pi}S$$
$$u = \mathrm{X} - 0.5772\alpha.$$

where S is the standard deviation and 7 is the mean. The mean and standard deviation of the flood peak as well as the parameters of the EV1 distribution were determined using 100 year time series of climate data with the rainfall runoff model. Using these statistics and the EV1 distribution, flood flows for the 2, 10, 50, and 100 year return periods were calculated.

Flooded area and severity

High river flows themselves are not a problem unless they overtop their banks and flood area in the adjoining flood plain. The determination of flood flows used the science of hydrology, while determining the extent of and depth of flooding was based on the science of hydraulics. Mirza et al. (2003) reported on the application of the MIKE11-GIS hydrodynamic model for Bangladesh to determine flooded area as a function of peak flood flows in the Brahmaputra–Ganges–Meghna rivers system. Their work supports a non-linear relationship that was develop between peak flow and flooded area with results in an R^2 of .59:

$$\text{Flooded area (million of hectares)} = 4.3095 * \ln[\text{Flow (cms)}] - 45.906$$

With a relationship between peak flow and flooded area, we have created a link between climate variables and the extent of flooding. Subsequent analysis of climate change will examine the impact of potential climate change on flooding in Bangladesh with full recognition of the possibility that this impact may not symmetric with respect to all levels of flood risk.

A hydrologic model for the rivers

Mirza et al. (2003) examined the potential climate change impacts for river discharges in Bangladesh using an empirical model to analyze changes in the magnitude of floods of the Ganges, Brahmaputra and Meghna Rivers. The present analysis uses a conceptual rainfall-runoff model, WATBAL, to analyze changes in the magnitude of floods for the same watershed. Yates (1997) describes the model. It has been applied in over forty country studies of climate change impact on runoff including the Nile River Basin, a river basin of the same spatial scale as the GBM basin.

More specifically, the WATBAL model predicts changes in soil moisture according to an accounting scheme based on the one-dimensional bucket conceptualization. Yates and Strzepek (1994) compared this relatively simple formulation to more detailed distributed hydrologic models and found them in close agreement with absolute and relative runoff. The advantage of this lumped water balance model lies in its use of continuous functions of relative storage to represent surface outflow, sub-surface outflow, and evapotranspiration in the form of a differential equation [see Kaczmarek (1993) or Yates (1996)]. The monthly water balance contains two parameters related to surface runoff and subsurface runoff. A third model parameter, maximum catchment water-holding capacity (Smax), was obtained from a global dataset based on the work of Dunne and Willmott (1996).

The precise structure of WATBAL is easily described. To begin with, the monthly soil moisture balance is written as:

$$S_{\max}\frac{dz}{dt} = R_s(P, z, t) - R_{ss}(z, t) - Ev(Pet, z, t) \tag{1}$$

where

P_{eff} = effective precipitation (length/time),
R_s = surface runoff (length/time),
R_{ss} = sub-surface runoff (length/time),
E_v = evaporation (length/time),
$S_{\max}$ = maximum storage capacity (length), and
z = relative storage $(1 \geq z \geq 0)$.

A non-linear relationship describes evapotranspiration based on Kaczmarek (1993):

$$E_v(z, Pet, t) = Pet\left(\frac{5z - 2z^2}{3}\right) \tag{2}$$

Following Yates (1996), surface runoff is described in terms of the storage state and the effective precipitation according to

$$R_s(z, P, t) = z^{\varepsilon}(P_{eff}) \tag{3}$$

where ε is a calibration parameter that allows for surface runoff to vary both linearly and non-linearly with storage. Finally, sub-Surface runoff is a quadratic function of the relative storage state:

$$R_{ss} = \alpha z^2 \tag{4}$$

where x is the coefficient for sub-surface discharge.

In certain regions, snowmelt represents a major portion of freshwater runoff and greatly influences the regional water availability. Ozga-Zielinska et al. (1994) provide a two parameter, temperature based snowmelt model was used to compute effective precipitation and to keep track of snow cover extent. Two temperature thresholds define accumulation onset through the melt rate (denoted mfi). If the average monthly temperature is below some threshold Ts, then the all the precipitation in that month accumulates. If the temperature is between the two thresholds, then a fraction of the precipitation enters the soil moisture budget and the remaining fraction accumulates. Temperatures above some higher threshold Tl give a mfi value of 0, so all the precipitation enters the soil moisture zone. If there is any previous monthly accumulation, then this is also added to the effective precipitation.

$$Peff_i = mf_i(A_{i-1} + Pm_i) \tag{5}$$

where,

$$mf_i = \begin{cases} 0 & \text{for} \quad T_i \le T_s \\ 1 & \text{for} \quad T_i \ge T_l \\ \frac{(T_i - T_s)}{(T_l - T_s)} & \text{for} \quad T_s < T_i < T_l \end{cases} \tag{6}$$

and snow accumulation is written as,

$$A_i = (1 - mf_i)(A_{i-1} + Pm_i) \tag{7}$$

In writing equations (5) through (7),

mf_i = melt factor,
A_i = snow accumulation,
Pm_i = observed precipitation,
$Peff_i$ = effective precipitation,
T_l = upper temperature threshold at which precipitation is all liquid (°C),
T_s = lower temperature threshold at which precipitation is all solid (°C), and
i = month.

The model was calibrated from the TYN CY 1.1 data for the Ganges and Brahmaputra separately over using data from monthly flow from the 1970 and 1980 and produced R^2 statistics of .89 and .87 for the Brahmaputra and Ganges, respectively. Since the climate change scenarios in COSMIC begin with a base year of 1990, the COSMIC base had to be correlated with the TYN CY 1.1 average data.

Notes:

1. The term ‘‘not-implausible’’ is a deliberate double negative designed to describe scenarios of future climate change that have (1) been produced by driving a respectable climate model with descriptions of plausible socio-economic futures and (2) have not be shown to be impossible by subsequent analysis. In a perhaps tortured use of the language, we feel that this definition distinguishes a range of ‘‘not-implausible’’ scenarios from what some would offer as a range of ‘‘plausible’’ scenarios.
2. COSMIC uses a distance weighting scheme for grid cells reported by the various global circulation models that it includes; as a result, the centroid values reported for a country like Nepal reflect more than one than one data point for each year. The hydrologic model, meanwhile, is designed to capture any non-monotonic shifts through its simulation of potential evapotranspiration and effective precipitation. As it has in other applications around the world, it can therefore pick up possible non-monotonic wetting or drying periods that might result from non-linear effects.
3. The adaptations discussed here are generic in the sense that they are described in terms of the protection that they would provide and not in terms of specific projects that have been or will be planned. The results are therefore to be interpreted as descriptions of effects that would weigh heavily on any cost-effectiveness, cost-benefit or risk management calculations of specific options that could be proposed

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